

TEMPERATURE AND RAINFALL TRENDS IN THE ATOYAC RIVER BASIN, OAXACA

Jesús Q. García-Santos, Laura Alicia Ibáñez-Castillo*, Ramón Arteaga-Ramírez, Mauricio Carrillo-García

Universidad Autónoma Chapingo. Posgrado en Ingeniería Agrícola y Uso Integral del Agua. Carretera México-Texcoco km 36.5, Chapingo, Estado de México, México. 56230.

*Corresponding author: libacas@gmail.com

ABSTRACT

In this work, we made an analysis of climatological data to identify trends in temperature and rainfall values in the Río Verde - Río Atoyac basin, in the state of Oaxaca. This information was analyzed using RCLimDex software to indicate the trends emerging over time. Apparently, there is a decrease in the number of cool days, an increase in cold nights, an increase in the duration of cold periods, and an increase in days with frost. A considerable increase was found in terms of consecutive dry days, an increase in the diurnal temperature range, an increase in the simple index of daily rainfall intensity, an increase in summer days, more hot days, longer duration of warm periods, and more extreme values, manifested in minimum and maximum temperatures.

In order to have a more complete overview, a long-term projection scenario (2075-2099) was analyzed. This revealed a decrease of about 4% in the forecast for precipitation for almost all months, an increase in the maximum temperature of up to 4.8 °C for October and an increase in the minimum temperature of up to 5.2 °C for October. The general conclusion, employing both approaches to analyze trends for measured data, considering theoretical long-term scenarios, is that temperatures will show a drastic increase, but a decrease in rainfall depth. Although within this trend, data analysis showed an increase in daily rainfall intensity.

Key words: climate change, climate indices, future climate scenarios, meteorological data in Mexico, RCLimDex.

INTRODUCTION

Climate consists of the average weather conditions over a period of 30 years or more. Average temperature and precipitation over a long period of time represent the principal variables that define climate (de la Fuente-Meraz and Olivera-Villaruel, 2018). Climate change consists of alteration in the Earth's climate, attributed directly or indirectly to human activity; it is a phenomenon that manifests itself in an increase in the average temperature of the planet (Díaz-Cordero, 2012). This alteration in the climate has repercussions at the magnitude of extreme temperature and precipitation events throughout the planet. According to the United Nations Framework Convention on Climate Change, this alteration is directly related to an increase in the emission of greenhouse gases into the atmosphere, resulting from human activities related to the use of fossil fuels (coal, natural gas and petroleum-derived fuels), as well as alterations in land use (deforestation) and decline in forests; these being two of the main reasons for this problem.

Scientists who have analyzed this climate behavior conclude that the climate will become more and more extreme. In general, summers will be hotter and rainfall patterns will be modified, with higher rainfall in some places and less frequent rainfall in others, thus increasing droughts (Bárcena *et al.*, 2015). Mexico is one of the most vulnerable countries

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to climate change, due to its geographical location, as it is surrounded by two oceans. In addition, its relief and the latitudes at which it is located, make it one of the most affected by temperature increase. The Intergovernmental Panel on Climate Change (IPCC) Group of Experts considers 27 extreme climate indices for temperature and precipitation. In many cases, the events that produce these values can have great impact on the environment (Mendoza-Aguilar, 2019).

The National Institute of Ecology and Climate Change (INECC, 2019) has indicated that out of the 2,456 municipalities into which the country is divided, 480 (20%) have a very high or high level of vulnerability to climate change. When observing these municipalities, evidently, the majority are located in the South of Mexico, among them the states of Oaxaca and Chiapas, which are characterized as constituting the poorest areas of the country. Likewise, according to the World Bank and the Organization for Economic Cooperation and Development (OECD), it is estimated that approximately 68% of the population and 71% of Mexican GDP are exposed to the adverse effects of climate change. According to the National Institute of Ecology and Climate Change (González *et al.*, 2021), when assessing vulnerability to climate change, adverse effects on: (a) human settlements exposed to landslides, floods and diseases, (b) on livestock production affected by water stress and floods, (c) vulnerability of forage production subject to water shortages.

This work aims to detect the presence or absence of climate change in one of the hydrological regions of the state of Oaxaca, in the Atoyac River area, which includes the state capital and other surrounding, poor municipalities.

THEORETICAL FRAMEWORK

In 1992, the United Nations (UN, 1992) held a conference on climate change, which defined climate change as alteration in climate that is attributed, directly or indirectly, to human activity. This alters the global composition of the atmosphere; change that is additional to natural climate variability, observed over the same time period. In 2021, the sixth report on climate by the Intergovernmental Panel on Climate Change (IPCC, 2021) defined climate change as a change in climate that can be identified using statistical tests to detect changes in the mean or variability of its properties over an extended period of time, typically at least decades. Likewise, in Annex VII of IPCC (2021), climate is defined as average weather conditions, in terms of mean and variability, over a period of at least 30 years. The most relevant variables that make up the climate are temperature, precipitation and wind. It is claimed that the climate is constantly changing, however, when statistically this presents a trend in any of its variables, we should pay attention, as this will affect ecosystems. For this reason, in 2010, the National Institute of Ecology proposed a guide for calculating climate change indices (Vázquez-Aguirre, 2010). In this work, 27 indices are proposed, which focus on the analysis of various forms of expression of rainfall and temperature. To apply this guide, RCLimDex software is very useful (Zhang *et al.*, 2018), as it statistically analyzes climate data over at least a 30-year period. The software searches

for statistical trends, based on the change in slope over time, of analyzed variables. It also assesses whether the change; increase or decrease, is significant or not significant, from a statistical point of view.

The World Meteorological Organization, with its Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI), developed 27 climate indices for the detection and monitoring of changes, referring to extreme climate records (Zhang *et al.*, 2018). Basically, the behavior of maximum and minimum temperatures and rainfall are analyzed over periods of at least 30 years. This methodology is based on the RCLimDex v1.9 software, which facilitates analysis of possible climate change. The Institute of Atmospheric Sciences and Climate Change (ICAyCC, 2023) maintains a website with possible climate change scenarios for Mexico in the short, medium and long term; it is constantly updated (<http://atlasclimatico.unam.mx/AECC/servmapas>). La Universidad Nacional Autónoma de México (UNAM), a través del ICAyCC, presents the scenarios for the CNRMCM5 from France, GFDL-CM3 from the United States and HADGEM2-ES from the United Kingdom.

Skepticism exists concerning whether climate change is really happening. The truth is that, in the last 8 years, the Pacific Ocean, off the Mexican coast, has presented two of the most extreme and damaging hurricanes; Hurricane Patricia in 2015 and Hurricane Otis in 2023, off the coasts of Colima and Guerrero, respectively (National Meteorological Service-SMN, 2023b). These hurricanes brought with them very heavy rainfall in the region and extraordinarily high temperatures were recorded at the ocean surface. In the study area of the Atoyac River in Oaxaca, where the capital of the state of Oaxaca is located, a change in the climate has been perceived by the population, which can only be confirmed by implementing a formal climate analysis. In this same area, there has also been a change in land use, another negative factor contributing to the occurrence of extreme climate scenarios. In this area, there has been major degradation of forest areas resulting from mostly illegal deforestation. During the period between 1980 and 2000, forest loss rates were assessed in the area, reaching around 24,000 hectares annually. This was particularly notable in areas such as Bajo Mixe, the Putla-Jamiltepec region and the Loxichas region. Deforestation is mainly attributed to changes in land use for agricultural activities, where the practice of slash-and-burn still persists (Ellis *et al.*, 2017).

In this work, the idea was always to carry out this climate trend analysis in the state of Oaxaca, given that this is a region with a depressed economy, so that adverse climate changes can affect these regions more, as its population will have fewer resources to remedy such adverse changes. However, the specific selection of the stations to be analyzed depended greatly on the availability of data reported by SMN (2023a); that is, we sought series of at least 30 years of data, with the lowest percentage of missing data. Meteorologists and statisticians recommend that missing data should not exceed 20%; however, in this work, which was considered to be more rigorous, we decided to only use series where missing data was less than 10%, and to fill in missing data, using the inverse square distance method (Campos-Aranda, 1998) for rainfall, which exhibits greater

temporal and spatial variability than temperature, although these missing data gaps could also be filled with digital data obtained from satellite images for rainfall and temperature (App Climate Engine, 2023). Within the App Climate Engine, we recommend using the CHIIRPS database for rainfall and the DAYMET database for maximum and minimum temperatures.

There is a recent previous work on precipitation trends in a region in the state of Guanajuato by Jaimes *et al.* (2021); however this only focused on precipitation analysis, without considering temperature, and only found small changes in rainfall, at two out of 18 meteorological stations.

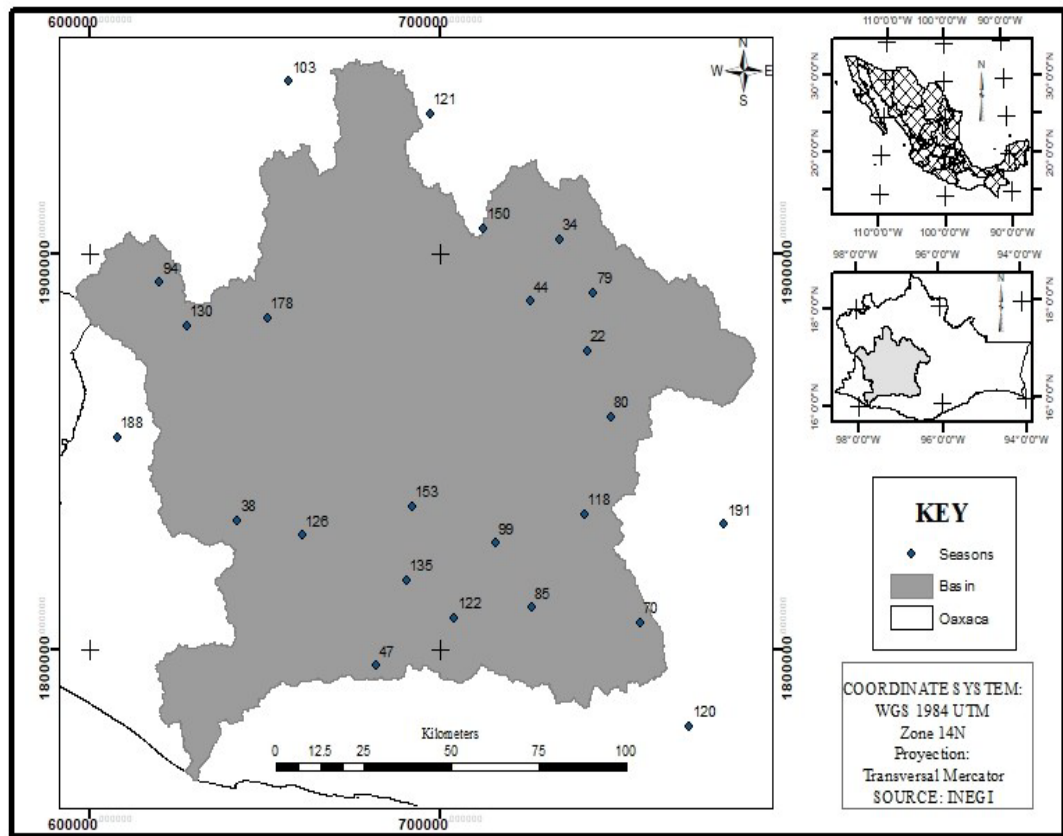
METHODOLOGY

In order to locate and characterize the basin where work took place, we had to refer to information from the National Institute of Statistics, Geography and Informatics (INEGI) of the Mexican Government. The Verde-Atoyac River basin is mostly located within the state of Oaxaca, between the coordinates 96° 16' 37" and 98° 05' 57" West Longitude and 17° 37' 20.32" and 15° 58' 46" North Latitude (Figure 1). The basin covers an approximate area of 18,261 km²; it belongs to hydrological region number 20, known as the Costa Chica of Guerrero (INEGI, 2008). Among the 243 municipalities located within the basin (Zorrilla *et al.*, 2017), of the most important ones, those that stand out include Oaxaca de Juárez, the capital city of the state and its surrounding municipalities, Ocotlán, Ejutla, Miahuatlán, Sola de Vega and Juchatengo, among others.

The altitude in the study area varies from 0 to 3,606 meters above sea level. Most of the basin has a sub-humid temperate climate (42.08 %), and secondly, 21.57% has a humid temperate climate (INEGI, 2008a). The average annual temperature is 20.2 °C; the coldest month is January, with an average monthly temperature of 18.9 °C, while May is the hottest month, with a monthly average of 22.9 °C. Average annual precipitation is 1,192 mm; daily rainfall is mostly less than 45 mm (SMN, 2023a). Records show some events with more than 200 mm of precipitation, but these are very scarce; these events are due to the passage of hurricanes on the coast, as was the case on October 8, 1997, when Hurricane Paulina made landfall in the Port of Santa Cruz and then continued its path through part of the study area, with records of more than 200 mm of precipitation.

The rainy season is mostly concentrated in the months of May to October, when the average maximum temperature varies from 31.1 °C to 34 °C and the average minimum temperature from 14.2 °C to 15.6 °C; during the rest of the year, the dry season, the average minimum temperature varies from 10.5 °C to 14.1 °C and the maximum ranges from 32.1 °C to 33.6 °C. Regarding land use and vegetation in the basin, annual rain-fed agriculture predominates with 18.65%, and then secondary oak forest with shrub vegetation at (11.42%) (INEGI, 2018). The predominant soil type in the area is eutrophic regosol, found in 62.74% of the basin, followed by lithosol, found in 15.15% of the area (INEGI, 2007).

In this work, we basically applied two methods: (a) climate analysis considering at least 30 years of historical information, available at meteorological stations and (b) climate



Source: self-elaborated with data from INEGI (2008b) and SMN (2023a).
Figure 1. Location of study area.

projection for a “distant” scenario, for the period 2075-2099 (ICAYCC-UNAM, 2023). From all the stations of the national meteorological system that are located within and around the work basin, we selected the following 29 climate stations for this project, as these passed through our filters and represent those for which a greater amount of information is available (Table 1).

Firstly, the necessary data was downloaded from the SMN website (2023a). The downloaded data included daily data on precipitation, maximum and minimum temperature, recorded at each of the meteorological stations, located both within the study area and in the surrounding area (SMN, 2023a). These included at least 30 years of information; preferably data that corresponded to the period between 1961 and 2019. On the National Meteorological Service website, where daily precipitation and temperature data are found, only data up to 2019 are published (2023a). We ensured that the data from the climatological stations did not present abnormal data or that more than 10% of data was missing, although the program can function with series that have a minimum of 70% of information (Zhang *et al.*, 2018).

Table 1. Meteorological stations referred to.

ID	Latitude	Longitude	Altitude	Rain-fall	Av temp	Municipality
20009	16.64	-95.96	639	549.3	25.9	Nejapa de Madero
20010	16.61	-98.15	420	2,095.8	26.7	San Juan Cacahuatpec
20018	17.25	-98.30	2,432	1,988.4	15.0	Coicayan de las Flores
20022	16.96	-96.70	1,504	552.8	20.1	San Bartolo Coyotepec
20034	17.03	-96.80	1,673	744.8	19.7	Villa de Etla
20038	16.57	-97.67	596	1,642.8	26.0	Santiago Ixtayutla
20044	17.07	-96.88	1,745	7,88.4	18.8	San Felipe Tejalapam
20047	16.23	-97.30	1,408	1,489.5	19.6	Santa Catarina Juquila
20070	16.33	-96.59	1,560	604.6	19.8	Miahuatlán de Porfirio Díaz
20079	17.08	-96.71	1,588	767.1	21.3	Oaxaca de Juárez
20080	16.80	-96.67	1,522	791.8	19.8	Ocotlán de Morelos
20085	16.37	-96.88	1,344	805.1	21.6	San Vicente Coatlán
20094	17.12	-97.87	1,321	2,519.3	24.1	Putla Villa de Guerrero
20099	16.51	-96.98	1,412	862.8	20.9	Santa Cruz Zenzontepec
20103	17.57	-97.52	2,313	731.0	15.4	San Andrés Lagunas
20118	16.58	-96.74	1,448	678.9	21.2	San Miguel Ejutla
20120	16.09	-96.46	2,457	1,281.3	14.5	San Miguel Suixhitepec
20121	17.50	-97.14	2,206	907.2	15.9	San Pedro Coxcattepec
20122	16.34	-97.09	861	908.1	24.6	San Pedro Juchatengo
20126	16.54	-97.49	960	1,387.8	23.7	Santa Cruz Zenzontepec
20130	17.02	-97.80	1,888	1,898.7	20.2	Santa María Yucuhiti
20135	16.43	-97.22	1,182	1,375.3	22.0	Santiago Minas
20141	17.50	-98.15	1,667	949.73	20.7	Silacayoapam
20150	17.23	-97.00	2,278	821.12	16.8	Santiago Tenango
20153	16.60	-97.20	1,778	2263.9	22.6	Santo Domingo Teojomulco
20178	17.03	-97.58	2,432	902.60	13.9	Chalcatongo de Hidalgo
20188	16.76	-97.99	355	1,731.2	26.4	Santa María Zacatepec
20191	16.55	-96.37	1,162	398.5	23.4	Santa María Zoquitlán
12061	16.68	-98.4	316	1,358.1	26.3	Ometepec, Guerrero

Source: SMN, (2023a).

Daily values are then processed in the RCLimDex software, with a prior basic quality control, intended to identify abnormal data, which fall outside the normal range of data obtained by the program, for example, one day, when the maximum temperature is lower than the average for the minimum temperatures or vice versa.

Next, an additional quality control is applied to identify very high or very low daily values, which are presumed to have been recorded incorrectly when the daily readings for precipitation and temperature were taken, for example, a day in which the minimum temperature appears as 21 °C, but in reality was 12 °C. To correct this information, an investigation is required to define whether there are records of days with very high temperatures or on the contrary, very low temperatures; and in the case of precipitation, whether there were days with such high rainfall levels; this is because the Oaxacan study area, whose lower section flows into the Pacific Ocean, is frequently affected by

the passage of hurricanes and tropical storms. If there is no information to corroborate the veracity of the recorded data, values that appear for that same day and that same variable, at stations close to the one you are working on, should be checked, in order to verify the veracity of the records or to conclude that an error occurred when the values were recorded.

The next step is data homogenization, which consists of verifying the trend for values, identifying gaps in the daily information or any other disruptive factor; the reason for lack of homogeneity in the data should be verified, whether this is because the location of the meteorological station was changed, or the equipment that takes the data was renewed, etc. To identify these inconsistencies, we suggest that the information be processed in the RHtests software, entered, using the same format as that used for the RClimDex program, following the procedure indicated by Wang and Feng (2013), and once the homogenized values are obtained, the calculation of the 27 basic climate change indices of ETCCDMI is undertaken; these appear in Table 2, where the first software is employed, as explained by Zhang *et al.* (2018).

Each of the 27 indices is plotted on a graph to observe whether there are increasing or decreasing trends, to what extent and whether these modifications indicate any presence of climate change at the meteorological station location.

Table 2. List of Indices for Core Climate Change, Detection and Monitoring (ETCCDMI), based on expert assessment.

Index	Descriptive name	Definition	Unit
SU25	Days of summer	Number of days a year that $XT > 25 \text{ }^\circ\text{C}$	Days
IDO	Days with frost	Number of days a year that $XT < 0 \text{ }^\circ\text{C}$	Days
TR20	Tropical nights	Number of days a year that $NT > 20 \text{ }^\circ\text{C}$	Days
FD0	Days below freezing	Number of days a year that $NT < 0 \text{ }^\circ\text{C}$	Days
GSL	Duration of growing season	Number of days a year between the first phase of minimum in the form of $GT > 5 \text{ }^\circ\text{C}$ the first phase after the 1° of July with, with a minimum of 6 days with $GT < 5 \text{ }^\circ\text{C}$	Days
TXx	Extreme maximum temperature	Annual maximum value of daily maximum temperature	$^\circ\text{C}$
TXn	Lowest maximum temperature	Annual minimum value of daily maximum temperature	$^\circ\text{C}$
TNx	Highest minimum temperature	Maximum annual value of the daily minimum temperature	$^\circ\text{C}$
TNn	Lowest minimum temperature	Annual minimum value of daily minimum temperature	$^\circ\text{C}$
Tx10p	Frequency of cool days	Percentage of days in which $XT <$ percentile 10	Days
Tx90p	Frequency of hot days	Percentage of days in which $XT >$ percentile 90	Days
Tn10p	Frequency of cold nights	Percentage of days in which $NT <$ percentile 10	Days
Tn90p	Frequency of hot nights	Percentage of days in which $NT >$ percentile 90	Days
WSDI	Duration of hot periods	Number of days of the year that as a minimum, there are 6 consecutive days with $XT >$ percentile 90	Days

Table 2. Continuation.

Index	Descriptive name	Definition	Unit
CSDI	Duration of cold periods	Number of days of the year that as a minimum, there are 6 consecutive days with NT < percentile 90	Days
DTR	Daily temperature range	Annual average for the difference between XT and NT	°C
Rx1day	Maximum precipitation in a day	Maximum annual value of the daily PPT	Mm
Rx5day	Maximum precipitation in 5 days	Annual maximum for PPT recorded on five consecutive days	Mm
SDII	Simple daily intensity index	Total annual precipitation divided by the number of days with PPT ≥ 1 mm	mm/día
R10	Days with rain exceeding 10 mm	Annual number of days in which PPT ≥ 10 mm	Days
R20	Days with rain exceeding 20 mm	Annual number of days in which PPT ≥ 20 mm	Days
R25	Days with rain exceeding 25 mm	Annual number of days in which PPT ≥ 25 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive days in a year with PPT < 1 mm	Days
CWD	Consecutive humid days	Maximum number of consecutive days in a year with PPT ≥ 1 mm	Days
R95p	Very humid days	Total annual precipitation (of days in which PPT ≥ 1 mm) when accumulated daily PPT exceeds the 95 percentile	Mm
R99p	Extremely humid days	Total annual PPT (of days in which PPT ≥ 1 mm) when accumulated daily PPT exceeds the 99 percentile	Mm
PRCPTOT	Total precipitation	Total annual PPT (of days in which PPT ≥ 1 mm	Mm

Where NT means minimum temperature, XT represents maximum temperature, GT is the average temperature, RR daily precipitation and TAP the total annual precipitation; the calculation of percentiles is carried out, taking the period 1961-1990 as the reference period.

Source: Zhang *et al.* (2018), Figueroa-Gallegos, (2017).

In order to complete the temporal vision of climatic trends in Oaxaca, climatic projections are made for a distant scenario (2075-2099), with the help of the climatic atlas of the Institute of Atmospheric Sciences and Climate Change (ICAYCC-UNAM, 2023). In this work, the CNRMCM5, GFDL-CM3 and HADGEM2-ES models were chosen, with which a forecast of the maximum and minimum temperatures and precipitation in the region was obtained. With this last information, a forecast is made of the risk faced by the flora, fauna and human population at this location, by that time. The complete methodology described above was implemented for each and every one of the meteorological stations studied.

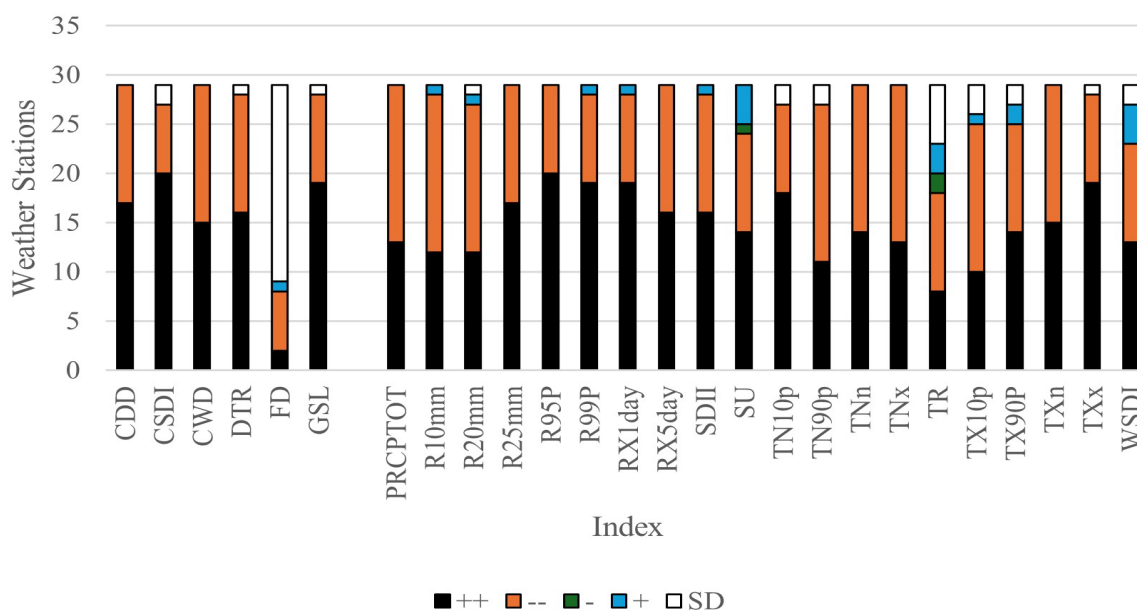
RESULTS

In the data series used, no records of negative precipitation were found, nor were there any maximum temperature values below the minimum.

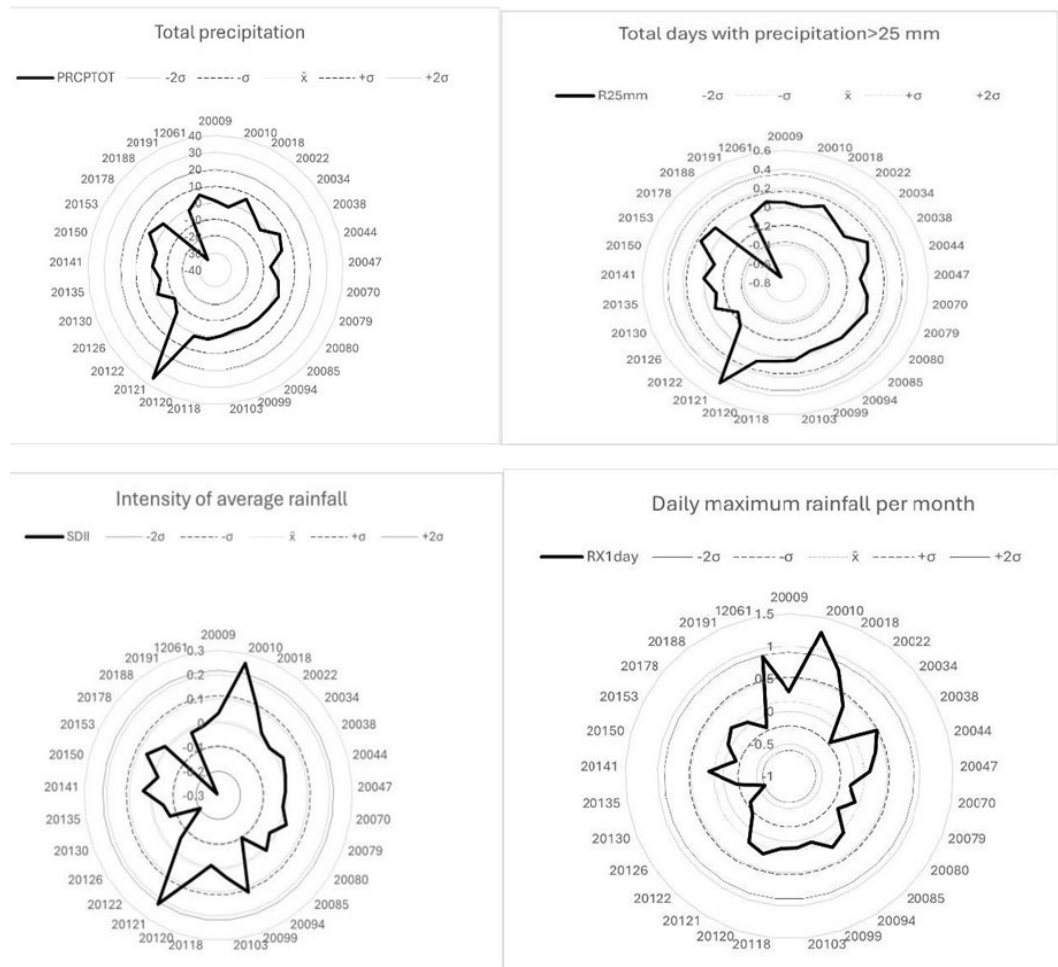
In the recorded precipitation data, as regards decimals, the use of zero and, to a lesser extent, five is overused, although 0.2, 0.3, 0.4, 0.6, 0.7, 0.8 and 0.9 are also taken into account, to some extent. As regards the recording of maximum and minimum temperatures, zero is used excessively, and to a lesser extent, 0.5, while the rest of the decimals are not taken into account at all, among any of the variables measured.

In Figure 2, for each climate change index, we present the number of stations that, with a 95% confidence level, show a non-significant positive trend (+), those that have a significant positive trend (++) , those that show a non-significant negative trend (-), as well as those where a significant negative trend is apparent (--). There are also stations for which, due to the amount of data available, we were unable to distinguish the trend line (TL), as experienced by Jaimes *et al.* (2021) and Figueroa-Gallegos (2017).

Evidently, for the most part, all indices show a significant upward trend, especially maximum temperatures coinciding with the amount of precipitation on a wet day, the number of cold nights, the average monthly difference between the maximum temperature and the minimum temperature, in addition to the number of days with levels exceeding 25 mm (Figure 3). On the contrary, a significant downward trend is apparent, mainly in terms of total annual precipitation and minimum temperatures, indicating a tendency towards more extreme climates.



Source: self-elaborated with information taken from RCLimDex.
Figure 2. Trends in climate change indices at the 29 stations.



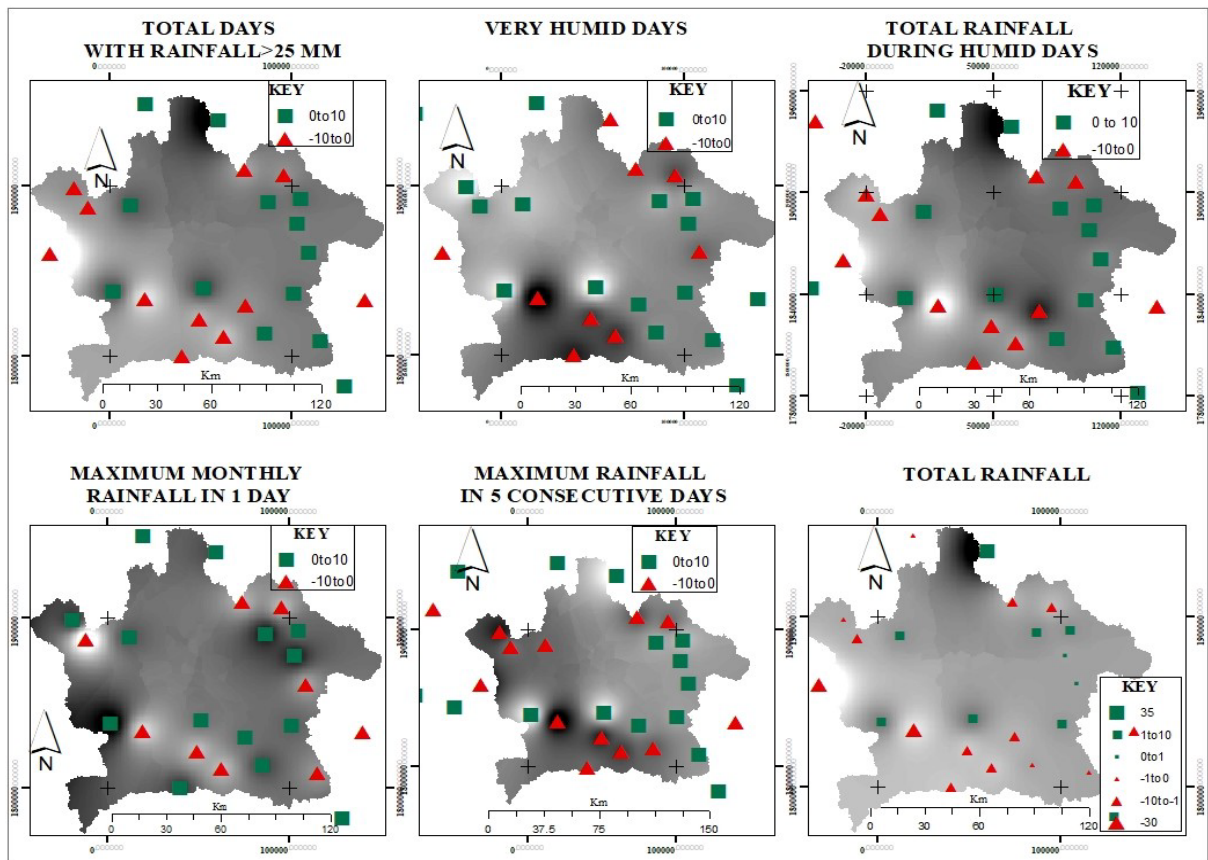
Source: self-elaborated based on data from SMN (2023a).

Figure 3. Average values for PROCTOR, R25mm, R95P, R99P and RX1day indices for each climate station analyzed.

Figure 3 is a radial graph showing the trends for some climatic indices related to precipitation. The numbers around the circle correspond to the seasonal climate key. The solid line shows the slope or rate of change per year for the index presented. The same graph shows confidence intervals measuring (a) one standard deviation (σ) and (b) two standard deviations (2σ); both limits, added or subtracted to that slope, are used to construct the upper and lower limits. For example, Figure 3a presenting the total annual precipitation at station 20,121 San Pedro Coxcaltepec, shows an increasing trend of approximately 35 mm/year (located at 2,206 masl, near Nochistlan, Oaxaca, semi-forested area) and station 20,188 Santa María Zacatepec, shows a decreasing trend of 32 mm/year (populated area, 355 masl). Similarly, Figure 3c can be interpreted and shows the rates of change in daily rainfall intensity. While most stations show a tendency towards increasing rainfall intensity, a few show a decrease in rainfall intensity.

In both Figure 3 and Figure 4, there is an apparent positive trend in climate in terms of precipitation. This means that, averaging the 29 stations analyzed each year, average annual precipitation increases by a minimal amount, the same situation that Kachok and Ivanova (2019) observed for the El Vizcaíno Biosphere Reserve, Baja California Sur. Evidently, greater daily rainfall levels are recorded, because each year, there are a greater number of hurricanes and tropical storms; consequently, this rainfall behavior, means that the rainy season is also reduced, resulting in annual precipitation, equal or greater than that of previous years, but now falling in fewer days, with greater daily rainfall levels, also affecting the simple index of daily rainfall intensity.

As for temperature, in Figures 5 and 6, the climate change indices that stand out in terms of a positive or negative trend, indicate that the maximum temperature among the maximums (TX_x), is undergoing a positive growth rate, which means that each year, higher maximum temperatures are presented, whereas contrarily, regarding the minimum temperatures (TN_n), each year colder days are recorded, compared to the previous year,



Source: self-elaborated based on data from SMN (2023a).

Figure 4. Trends in climate change indices for precipitation at the stations.



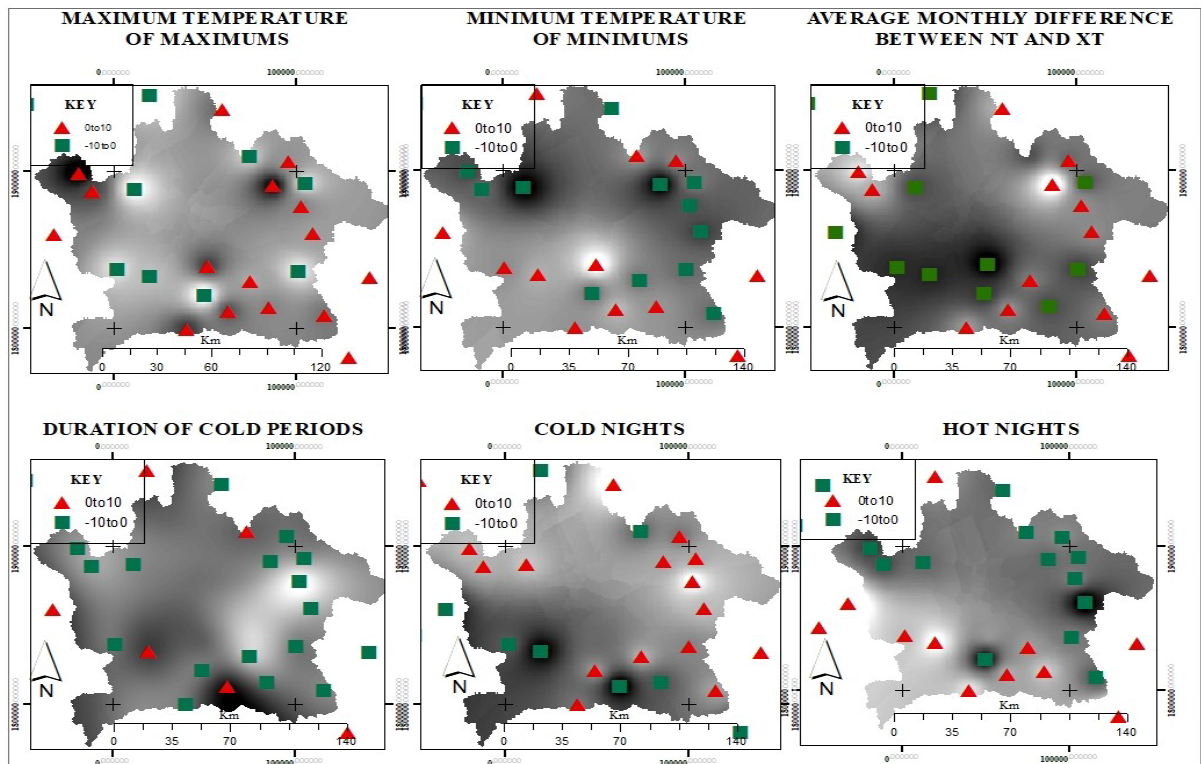
Source: self-elaborated based on data from SMN (2023a).

Figure 5. Average values for temperature-related indices for each climatological station analyzed.

meaning that temperatures are becoming increasingly extreme. Figure 5a presents a number of stations with a tendency for their maximum temperature to increase. In some stations, the annual rate of increase will be up to $0.2\text{ }^{\circ}\text{C}/\text{year}$. In contrast, in Figure 5b, the rates of change for minimum temperatures are presented.

This trend in extreme temperature values is manifested in the Tn10P index, which presents the number of cold nights in a year (Figure 5d), also increasing with respect to previous data and, contrastingly, the Tn90P index, also presents the warm nights in a year (Figure 5c), showing a negative slope, indicating that minimum temperatures, which generally occur at night, have been decreasing.

As for the Tx10P index, which analyzes cold days, this presents a negative slope, indicating that the temperature during the day is higher each year compared to the previous one; and the Tx90P, responsible for counting hot days, shows a positive slope, indicating that each year, higher maximum temperatures are being recorded. Likewise, all of the above concurs with the positive slope for the DTR index, or diurnal temperature range, which shows



Source: self-elaborated based on data from SMN (2023a).
Figure 6. Temperature-related climate change indices.

the difference between the maximum and minimum temperature, because the minimum temperature will be increasingly lower and the maximum temperature, increasingly higher, manifested in greater differences, somewhat similar to that shown by De la Mora-Orozco *et al.* (2016), for the state of Chiapas.

For the climate projection, data from the UNAM website <http://atlasclimatico.unam.mx/AECC/servmapas> were applied to the French CNRMCM5, American GFDL-CM3 and United Kingdom HADGEM2-ES models. Data were obtained, one by one, from each of the servmapas images for each month, showing precipitation, as well as minimum and maximum temperatures.

In Table 3, the three models analyzed (French, United States and United Kingdom), indicate a slight decrease in the amount of monthly rainfall, particularly in the United Kingdom model, compared to the current average monthly rainfall (the one used from the stations in the study area), which ultimately results in a very slight decrease in the average annual rainfall forecast for the distant future (2075-2099), compared to the current average annual millimeters. Only one abnormal figure is forecast with the United Kingdom model for the month of November, showing a much higher level than that predicted for the other two, higher than the current average level, even than that shown by the same model for the month of October. In the same Table 3, the penultimate row,

Table 3. Annual precipitation forecast for a distant scenario 2075-2099.

Rain	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Now	7	13	20	38	114	239	205	234	250	127	22.4	8.6
France	5	17	16	39	146	214	173	214	243	117	19	7
EUA	5	20	15	28	99	245	178	204	231	142	44	17
UK	8	18	14	25	104	222	177	184	194	71	132	29
Prm fut	6	18	15	30.	116	227	176	200	223	110	65.	18
Dif fut	1	-4.2	5	7.5	-2.2	12.9	29.6	34	27.3	17	-42.6	-9.2

Source: self-elaborated based on data from <http://atlasclimatico.unam.mx/AECC/servmapas>.

“Prm fut”, presents the average for the three forecast future models, and the last row, “Dif fut”, represents the difference between the current monthly value and the forecast for the future average. So, as far as rainfall for the distant scenario is concerned, there is an average 4% reduction, compared to the current average.

Table 4 shows a comparison between the current monthly maximum temperature and the one forecast by each of the three models presented above. Apparently, the temperature forecast by the models increases the most in the US and UK models, by almost 4 °C each month, and to a lesser extent in the French model, which shows an increase of around 3 °C. In general, for the long-term scenario, there will be maximum temperature increases of up to 4.8 °C for the month of October and a minimum increase of 2.6 °C for January. Table 5 presents a comparison between the current monthly minimum temperature and the temperature forecast for each of the three models studied above. The temperature forecast by the models is expected to increase by almost 4°C each month, with the French model forecasting a rise of around 3 °C. In general, minimum temperatures will increase by between 3.9 °C for January and 5.2 °C for October.

DISCUSSION

When analyzing the meteorological data, a future increasing trend was observed in both maximum (up to almost 4 °C) and minimum (around 3 °C) temperatures, while currently, there are more and more days with high temperatures, fewer days with low temperatures, a

Table 4. Forecast of maximum temperature for a distant scenario 2075-2099.

T°C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Now	20	20.9	21.8	22.2	21.4	19.8	20	19.4	19	19.6	20.4	20.3
France	20.6	21.6	22.1	23.2	22.7	19.8	20.7	20	20.3	22.1	22.7	22.9
EUA	23.2	24.8	26	26.6	26.3	25.2	24	25.3	24.7	25.3	23.9	24.4
UK	24.1	24.7	26.3	26.8	26.7	24.7	24.8	26.6	25.5	25.7	23.9	24.4
Prm fut	22.6	23.7	24.8	25.5	25.2	23.2	23.2	24	23.5	24.4	23.5	23.9
Dif fut	2.6	2.8	3	3.3	3.8	3.5	3.2	4.5	4.5	4.8	3.1	3.58

Source: self-elaborated based on data from <http://atlasclimatico.unam.mx/AECC/servmapas>.

Table 5. Forecast for minimum temperature in a distant scenario 2075-2099.

T °C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Now	7.3	7.5	8.0	8.8	9.4	9.2	9.2	9.1	9.2	8.9	8.5	7.8
France	10	10.4	11.3	12.4	13.1	13.3	12	12.8	12.9	12.8	11.8	10.4
EUA	11.2	11.4	12.3	13.3	15.5	15	14.5	13.4	14.1	15	13.4	12.9
UK	12.3	12.5	12.5	13.6	14.5	14.4	14.6	15	15.5	14.5	13.8	13.1
Prm fut	11.2	11.4	12.0	13.1	14.4	14.2	13.7	13.7	14.2	14.1	13.0	12.1
Dif fut	3.9	4.0	4.0	4.3	4.9	5.1	4.5	4.6	5.0	5.2	4.5	4.4

Source: self-elaborated based on data from <http://atlasclimatico.unam.mx/AECC/servmapas>.

greater presence of cold periods and these show increasing duration, with an increasingly greater difference between the maximum and minimum temperature, a greater number of cold nights, less occurrence of warm nights, a greater presence of periods with hot days, lasting longer each time, as concluded by Velasco-Hernández *et al.* (2015) for Ciudad Serdán in Puebla.

Regarding precipitation, on average it was apparent that there is no significant tendency towards an increase, as concluded by Zarazúa-Villaseñor *et al.* (2014) for the southern Gulf Coast of Mexico, because in some stations, there is a positive tendency, but for the remainder, the tendency is negative. Considering the rest of the indices, an increase is observed in the number of days in a year when precipitation exceeds 25 mm (Figure 3b), likewise there is an increase in the number of consecutive dry days, a greater number of consecutive wet days, increasingly wet days, a greater amount of precipitation in one day, a greater amount of precipitation in five consecutive days, a decrease in rainy days, a decrease in the number of days with low rain fall levels and a greater occurrence of torrential rain.

CONCLUSIONS

In the state of Oaxaca, a lack of data was detected that made it impossible to analyze climate change in some regions. Finally, this area represented the basin, in the state of Oaxaca that provided the most complete historical series of climate data.

Apparently, out of the 27 indices analyzed at the 24 meteorological stations, there is a significant upward trend in terms of the following indices: increase in maximum temperatures, increase between the difference between minimum and maximum temperatures in a month, an increase in days with daily rainfall exceeding 25 mm and an increase in the simple index of daily rainfall intensity. A considerable increase in consecutive dry days was also found. In short, rainfall tends to be more intense but there are longer periods of drought.

The long-term projection (2075-2099), evidently forecasts a new monthly distribution of rainfall throughout the year, an increase in the maximum temperature and an increase in the minimum temperature, that is, a more extreme climate. Therefore, considering the analysis of the historical data from 29 stations and their respective long-term projections,

we conclude that tendencies towards climate change definitely exist in the Atoyac River basin, Oaxaca.

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REFERENCES

- Bárcena A, Prado A, Samaniego J, Pérez R. 2015. El cambio climático: evidencia y escenarios futuros. *In*: La economía del cambio climático en América Latina y el Caribe. Santiago de Chile, 1a Ed. ONU: Santiago de Chile. <https://repositorio.cepal.org/server/api/core/bitstreams/ca0445d3-e3f3-4f40-a5ff-057a9a34f016/content>. pp: 15-21.
- Campos, FD. 1998. Procesos del Ciclo Hidrológico, capítulo 4 Precipitación: págs. 12-18. Universidad Autónoma de San Luis Potosí. México.
- Climate Engine Organization. 2023. App Climate Engine. <https://app.climateengine.org/login>. Fecha de consulta marzo 2023.
- De la Fuente-Meraz A, Olivera-Villarreal S. 2018. El Cambio Climático en México. *In*: Impactos socioeconómicos del cambio climático en México, 1ª Ed.; UAM, CDMX, México. . http://dccd.cua.uam.mx/libros/investigacion/cambio_climatico_impactos_socioeconomicos.pdf. 19 P.
- De la Mora-Orozco C, Ruiz-Corral J, Flores-López H, Zarazúa-Villaseñor P, Ramírez-Ojeda G, Medina-García G, Chávez-Durán A. 2016. Índices de cambio climático en el estado de Chiapas, México, en el periodo 1960-2009. *Revista Mexicana de Ciencias Agrícolas* (13). 2523-2534. <https://www.scielo.org.mx/pdf/remexca/v7nspe13/2007-0934-remexca-7-spe13-2523-en.pdf>.
- Díaz-Cordero G. 2012. El cambio climático. *Ciencia y sociedad*, XXXVII: 227-240. <https://www.redalyc.org/pdf/870/87024179004.pdf>.
- Ellis A, Romero-Montero J, Hernández-Gómez I, Anta-Fonseca S, López-Paniagua J. 2017. Deforestación y sus determinantes. *In*: Determinantes de la deforestación en el estado de Oaxaca. Alianza México para la reducción de emisiones por deforestación y degradación: Ciudad de México: Agencia de los Estados Unidos para el Desarrollo Internacional (USAID), The Nature Conservancy (TNC). <https://sis.cnf.gob.mx/wp-content/plugins/conafor-files/2018/nacional/catalogo/biblioteca/192.pdf>. pp: 9-28.
- Figuroa-Gallegos J. 2017. Índices de cambio climático en la cuenca del Río Grande, Chiapas, México. *Tecnología y Ciencias del Agua*, VIII(6). 137-143. <https://doi.org/10.24850/j-tyca-2017-06-10>
- González D, Vermonden A, Gress F. 2021. Municipios Vulnerables al cambio climático con base en los resultados del Atlas Nacional de Vulnerabilidad al Cambio Climático. INECC. 60 p.
- INECC. 2019. Atlas Nacional de Vulnerabilidad al Cambio Climático México. 1ª. Edición (libro electrónico). Instituto Nacional de Ecología y Cambio Climático. México. Disponible en: https://atlasvulnerabilidad.inecc.gob.mx/page/fichas/ANVCC_LibroDigital.pdf.
- Instituto de Ciencias de la Atmósfera y Cambio Climático UNAM. 2023. Actualización de los escenarios de cambio climático para estudios de impactos, vulnerabilidad y adaptación. <https://atlasclimatico.unam.mx/cmip5/visualizador>.
- INEGI. 2007. Conjunto de Datos Vectorial Edafológico. Escala 1:250 000 Serie II Continuo Nacional Oaxaca. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825235291>.
- INEGI. 2008a. Conjunto de datos vectoriales escala 1:1 000 000. Unidades climáticas. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267568>.
- INEGI. 2008b. Red hidrográfica edición 2.0. Cuenca R. Atoyac. Región H. Costa Chica - Río Verde. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825006894>.
- INEGI. 2018. Conjunto de datos vectoriales de uso del suelo y vegetación. Escala 1:250 000. Serie VII. Conjunto Nacional. <https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=889463842781>.
- IPCC (Intergovernmental Panel on Climate Change). 2021. Climate Change 2021 The Physical Science Basis. Working Group Contribution to the Sixth Assessment Report for the IPCC.
- Jaimes J, Ibáñez L, Arévalo G, Vázquez M, Monterroso A. 2021. Tendencias en la precipitación diaria de la cuenca alta Laja-Peñuelitas, Guanajuato. *Revista Mexicana de Ciencias Agrícolas*, 12(7). <https://doi.org/10.22231/asyd.v21i4.1663>

- org/10.29312/remexca.v12i7.2919.
- Kachok R, Ivanova A. 2019. Índices de cambio climático en la reserva de la biósfera el Vizcaíno, Baja California Sur, México (1960-2012). *Revista Brasileña de Climatología*, 24, 67-93. <http://dx.doi.org/10.5380/abclima.v24i0.51845>.
- Mendoza-Aguilar B. 2019. Homogeneización de datos climáticos y análisis de eventos extremos de precipitación en la zona del monzón de América del Norte. Tesis para obtener el título de Maestría en Ciencias en Oceanografía Física, Centro de Investigación Científica y de Educación Superior de Ensenada, Baja California (CICESE), Ensenada, Baja California, México, 2019 https://cicese.repositorioinstitucional.mx/jspui/bitstream/1007/2783/1/Tesis_Brenda_Yutziny_Mendoza_Aguilar_21feb2019.pdf.
- SMN. 2023a. Información Estadística Climatológica. Recuperado el 31 de 10 de 2023, de <https://smn.conagua.gob.mx/es/climatologia/informacion-climatologica/informacion-estadistica-climatologica>.
- SMN, 2023b. Ciclones tropicales en el océano Pacífico y en el Océano Atlántico en México. Recuperado el 2 de noviembre de 2023 de <https://smn.conagua.gob.mx/es/ciclones-tropicales/informacion-historica>.
- UNITED NATIONS. 1992. United Nations Framework Convention on Climate Change. <https://unfccc.int/resource/docs/convkp/conveng.pdf>. 25 p.
- Vázquez-Aguirre J.L. 2010. Guía para el cálculo y uso de índices de cambio climático en México. INEC. México. 88 p.
- Vázquez-Aguirre J, Brunet MD, Jones P. 2008. Cambios observados en los extremos climáticos de temperatura y precipitación en el estado de Veracruz, México a partir de datos diarios. *Asociación Española de Climatología*, 447-456. <http://hdl.handle.net/20.500.11765/8657>.
- Velasco-Hernández M, Morales-Acoltzi T, Estrella-Chulim N, Díaz-Ramos R, Juárez-Sánchez J, Hernández-Vázquez M, Bernal-Morales R. 2015. Tendencias y variabilidad de índices de cambio climático: enfoque agrícola en dos regiones de México. *Revista Mexicana de Ciencias Agrícolas*, 6(7). 1587-1599. <https://www.scielo.org.mx/pdf/remexca/v6n7/v6n7a13.pdf>.
- Wang X, Feng Y. 2013. ETCCDI Climate Change Indices. Obtenido de <https://etccdi.pacificclimate.org/software.shtml>.
- Zarazúa-Villaseñor P, Ruiz-Corral J, Ramírez-Ojeda G, Medina-García G, Rodríguez-Moreno V, de la Mora-Orozco C, Durán-Puga N. 2014. Índices de extremos térmicos en las Llanuras Costeras del Golfo Sur en México. *Revista Mexicana de Ciencias Agrícolas*, (10). 1843-1857. <https://www.scielo.org.mx/pdf/remexca/v5nspe10/2007-0934-remexca-5-spe10-1843-en.pdf>.
- Zhang X, Feng Y, Chan R. 2018. Introduction to RCLimDex v1.9. Climate Research Division, Downsview, Ontario, Canada. <https://github.com/ECCC-CDAS/RCLimDex/blob/master/inst/doc/manual.pdf>.
- Zorrilla M, De la Lanza G, González I, Martínez A, Hernández S. 2017. Área de estudio. *In: Enfoque integrado ambiental de la determinación del caudal ecológico y su asociación con la conservación de cuencas hidrográficas: ejemplo de caso río Verde Atoyac, en el Estado de Oaxaca*, 1ª Ed. Universidad Autónoma de Campeche, Campeche, México.